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**RADIATIVE DECAY OF MASSIVE NEUTRINOS:
IMPLICATIONS FOR PHYSICS AND ASTROPHYSICS***

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ABSTRACT:

This paper reports work with R. W. Brown where the radiative lifetime τ for the decay of massious neutrinos is calculated using various physical models for neutrino decay. The results are then related to the astrophysical problem of the detectability of the decay photons from cosmic neutrinos. Conversely, the astrophysical data are used to place lower limits on τ . These limits are all well below predicted values. However, an observed feature at $\sim 1700 \text{ \AA}$ in the ultraviolet background radiation at high galactic latitudes may be from the decay of neutrinos with mass $\sim 14 \text{ eV}$. This would require a decay rate much larger than the predictions of "standard" models but could be indicative of a decay rate possible in composite models. We may thus have found an important test for substructure in leptons and quarks.

I. INTRODUCTION

While suggestions tying astrophysical observations with the possibility of massious¹ neutrinos have been around for some time², the advent of grand unification theories³ and (as we will suggest here) composite models of quarks and leptons⁴ as well as recently reported experimental results implying finite⁵ and cosmologically significant⁶ neutrino masses, are stimulating much interest and work on the subject of massious neutrinos and their cosmological implications⁷. Some of these implications will be discussed by others at this symposium. We will concentrate on aspects involving the astrophysical search for radiation from the decay of massious neutrinos. We begin with a brief summary of the basic cosmological setting for a discussion of this topic.

II. COSMOLOGICAL SETTING

Since the radiative lifetimes of light massious neutrinos are expected to be much larger than the age of the universe, both from theoretical⁸ and some observational⁹ considerations, one must look for the most copious source of neutrinos in the universe in order to look for photons from their decay. This source is the big-bang itself¹⁰. For each neutrino flavor f and helicity ϵ_f , the number density of neutrinos plus antineutrinos in the universe is

$$n_{\nu_{f\epsilon}} = 1.1 \times 10^2 \left(\frac{T}{2.7K} \right)^3 \text{ cm}^{-3} \quad (1)$$

The total number density is thus

$$n_{\nu} = 110 \sum_f g_f \quad (2)$$

taking $T = 2.7K$ and the total mass is

$$\Sigma_v = 110 \Sigma_g m_{\nu_f} \quad (3)$$

Denoting $\Omega_v = \Sigma_v / \rho_c$ the fraction of the closure density of the universe in neutrinos, it follows that

$$\Omega_v = 0.01 h_0^{-2} \Sigma_v \quad (4)$$

where h_0 is the present Hubble constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and Σ_v is in eV. Thus a value for $25 < \Sigma_v < 100 \text{ eV}$ could close the universe ($0.5 < h_0 < 1$). We may compare equation (4) with the various values of Ω associated with objects on different astronomical scales. It has been found that the ratio of mass-to-light based on dynamical mass measurements increases with the increasing scale size. It is found that over distances much larger than typical interstellar scales, M/L is proportional to scale size ($M/L \propto r$) up to distances of the order of Mpc^{11} . Our version of Figure 2 of reference 11, which takes account of additional data¹² (in general agreement with that in reference 11) is shown in Figure 1. The curve shown in Figure 1 gives a functional approximation to the data of the form

$$(M/L) = \mu_0 [1 - \exp(-r/\Lambda)] \quad (5)$$

in solar units. At extragalactic distances, the h dependence is also shown on the scale. The function (5) has the virtue that $M/L \propto r$ for $r \ll \Lambda$ and $M/L \rightarrow \text{const}$ for $r \gg \Lambda$ as required by the observational constraint $\Omega \lesssim 2$. The value for M/L corresponding to the critical density (i.e., $\Omega = 1$) is shown by

the circle marked C. It can be seen that there appears to be a scale size $\Lambda \sim$ a few Mpc which is characteristic of the non-luminous mass in the universe. This size is interestingly close to the galaxy clustering size $\sim 4 \text{ Mpc}^{13}$ and is of the order of the Jeans length (scaled to the present time) which one would obtain from the growth of gravitational perturbations of neutrinos in the range¹⁴

$$\text{a few eV} \lesssim m_\nu \lesssim \text{a few tens of eV} \quad (6)$$

This range of masses is also relevant to the dynamical studies of Tremaine and Gunn¹⁵. It should also be noted that cosmological neutrinos can undergo violent relaxation¹⁶ to produce a density distribution $n_\nu \propto r^{-2}$ as implied by rotation curve studies of the outer parts of galaxies (halos) and that such a density distribution, when extrapolated to galaxy clusters, can give the observed relation $M/L \propto r$. It may also be noted that massious neutrinos in the mass range (6), could close the universe (see equation (4)) and thereby solve the "flatness problem" proposed by Guth¹⁸. Without getting into such controversial areas as to whether or not $\Omega = 1$ or whether neutrinos cluster on the scale of galaxy clusters, galaxy halos, or both¹⁹, we will therefore concentrate our further discussion on the radiative decay of neutrinos in the mass range (6) and the consequences of searching for the decay photons.

III. ASTROPHYSICAL NEUTRINO FLUXES AND RADIATIVE LIFETIMES

It has been pointed out by De Rújula and Glashow⁸ that the wavelength range to search for photons from the decay of cosmologically produced neutrinos (mass range given by (6)) lies in the far ultraviolet. This is

because for the decay from a heavier (ν') to a lighter mass (ν) neutrino

$$\nu' \rightarrow \nu + \gamma \quad (7)$$

the emitted photon has an energy

$$E_0 = \frac{m'^2 - m^2}{2m'} \quad (8)$$

in the rest system of the decaying neutrinos.

The neutrinos have been "adiabatically cooled" by the expansion of the universe so that their velocity spread is determined by the dynamics of their gravitational interaction rather than by thermal velocities. Typical velocities for neutrinos bound in galaxy halos would be ~ 300 km/s. For neutrinos in galaxy clusters, the dynamical velocities would be $\sim 10^3$ km/s. Thus, for E_0 corresponding to a wavelength $\lambda_0 \sim 1000 \text{ \AA}$ ($E_0 \sim 12\text{eV}$) the Doppler spread of the lines would be $\Delta\lambda \sim 1 \text{ \AA}$ for neutrinos in galaxy halos and $\sim 3 \text{ \AA}$ for neutrinos in galaxy clusters ($\Delta\lambda/\lambda_0 \sim v_v/c$). For the case where $m' \gg m$, which might be expected in light of the large mass differences known to exist among the charged leptons, equation (8) reduces to

$$E_0 \approx m'/2, \quad m' \gg m \quad (9)$$

In contrast to the narrow monochromatic radiation expected from nearby objects, there should also be continuum radiation at $E < E_0$ ($\lambda > \lambda_0$) from the decay of neutrinos which occurred in the past when we integrate the line emission over all redshifts.

The formulas for the astrophysical photon fluxes are as follows²⁰:

- 1) The diffuse line intensity from the galactic halo is given by

$$I_{\lambda} = \frac{1}{4\pi\tau\Delta\lambda} \int n' dl \quad \text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ \AA}^{-1} \quad (10)$$

where τ and n' are the lifetime and density of ν' neutrinos and the integral is along the line-of-sight of the telescope.

- 2) The flux from an extragalactic source such as the halo of a nearby galaxy or a nearby galaxy cluster is given by

$$F_{\lambda} = \frac{1}{4\pi R^2 \tau \Delta\lambda} \int n' dV = \frac{N}{4\pi R^2 \tau \Delta\lambda} \quad \text{cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1} \quad (11)$$

where the volume integral

$$N = \int n' dV \quad (12)$$

gives the total number of ν' neutrinos in the source and R is the distance to the source. If the mass of a galaxy cluster or halo is assumed to be mainly from ν' neutrinos, then

$$N = \frac{2. \times 10^{66} (M_s/M_{\odot})}{m'(\text{eV})} \quad (13)$$

where M_s is the total mass of the source, usually given in solar mass (M_{\odot}) units.

3) The continuum flux from the decay of cosmological neutrinos is

$$I(E) = \frac{c}{4\pi H_0} \frac{n'_0}{\tau} \int_0^{z_c} dz \frac{\delta[(1+z)E-E_0]}{(1+z)(1+\Omega z)^{1/2}} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ eV}^{-1} \quad (14)$$

where z_c is the critical redshift of absorption of the UV flux.

Since $E = K/\lambda$ where $K = 1.24 \times 10^{-5} \text{ eV } \text{\AA} = hc$, in wavelength units and for

$\lambda_0 = hc/E_0$, equation (14) becomes

$$I_\lambda = \frac{cn'_0}{4\pi H_0 \tau} \frac{\lambda_0^{3/2}}{\lambda^{5/2}} [1 + (\Omega-1)(1-\lambda_0/\lambda)]^{-1/2} \quad (15)$$

$$\lambda_0 < \lambda < \lambda_0(1+z_c)$$

or, in numerical units²¹.

$$I_\lambda = 7.8 \times 10^{28} h_0^{-1} \tau^{-1} \frac{\lambda_0^{3/2}}{\lambda^{5/2}} [1 - (\Omega-1)(1-\lambda_0/\lambda)]^{-1/2} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ \AA}^{-1} \quad (16)$$

Since the expected ultraviolet fluxes (10), (11) and (16) are proportional to the neutrino decay rate τ^{-1} , the physics of neutrino decay (τ for $\nu' \rightarrow \nu + \gamma$) and the astrophysical observations are both related to the problem of determining the lifetime of putative massless neutrinos in the mass range (6).

IV. MODELS FOR RADIATIVE NEUTRINO DECAY

To compute the radiative neutrino decay rate $\Gamma = \tau^{-1}$, we first note that the most general form for the amplitude is

$$T(\nu' + \nu + \gamma) = i \frac{g}{\Lambda} \bar{\Psi}(p-q) \sigma_{\mu\nu} \epsilon^{\mu\nu} (a + b\gamma_5) \Psi(p) \quad (17)$$

where $p^2 = m'^2$, $(p-q)^2 = m^2$. a and b are dimensionless numbers while Λ characterizes the relevant mass scale, or combination of mass scales, involved in the decay interaction. Equation (17) follows from gauge and Lorentz invariance and leads to the decay rate

$$\Gamma = \frac{g^2}{2\Lambda^2} \left(\frac{m'^2 - m^2}{m'} \right)^3 (|a|^2 + |b|^2) \quad (18)$$

If $m' \gg m$,

$$\Gamma = 3.65 \times 10^{-21} \frac{[m'(\text{eV})]^3}{[\Lambda(\text{GeV})]^2} (|a|^2 + |b|^2) \text{ eV} \quad (19)$$

or

$$\tau = 1.30 \times 10^5 \frac{[\Lambda(\text{GeV})]^2}{[m'(\text{eV})]^3} (|a|^2 + |b|^2)^{-1} \text{ sec.} \quad (20)$$

Equation (20) is the basis for a discussion about the lifetimes predicted in various models. The models have a wide range of characteristics, and it is useful to characterize them by the parameters a , b , and M .

A. Conservative GWS

It may yet turn out that neutrinos really are massless and hence do not oscillate, as in the standard Glashow-Weinberg-Salam (GWS) model with no right-handed neutrinos. In this case, $a = b = 0$, and

$$\tau = \infty \text{ (GWS)} \quad (21)$$

and there would be no more story to tell. This would also be the case for massless neutrinos with conserved lepton number (flavor).

B. Extended GWS

On the other hand, it is easy to extend GWS to include neutrino masses and mixing. (The mass eigenstates ν_i differ from the weak-interaction basis ν_ℓ .) Neutrino electromagnetic decay can now proceed by an intermediate state consisting of a weak boson W and a charged lepton ℓ both of which can couple to the photon (see Figure 2). For three generations ($i = 1, 2, 3$; $\ell = e, \mu, \tau$) of Dirac neutrinos, and for $m_3 > m_1$, for example, the $\nu_3 \rightarrow \nu_1 + \gamma$ decay rate is²²

$$\Gamma(\nu_3 \rightarrow \nu_1 + \gamma) = \frac{9G_F^2 \alpha}{2048\pi^4} \left(\frac{m_3^2 - m_1^2}{m_3} \right)^2 (m_3^2 + m_1^2) \times \left[\frac{m_\tau^2 s_2^2 + m_\mu^2 c_2^2 - m_e^2}{M_W^2} s_1 c_1 s_3 - \frac{m_\tau^2 - m_\mu^2}{M_W^2} s_1 s_2 c_2 c_3 \right]^2 \quad (22)$$

in terms of the Kobayashi-Maskawa-like neutrino mixing angles ($s_i \equiv \sin \theta_i$, $c_i \equiv \cos \theta_i$) with no CP violation. For a general $\nu' \rightarrow \nu + \gamma$, the scale is

$$\Lambda = (G_F m')^{-1} = \frac{10^{14}}{m'(\text{eV})} \text{ GeV} \quad (23)$$

and the numbers a and b are (ignoring s_i , c_i factors)

$$|a|, |b| = \frac{3}{32\pi^2} \frac{m_\tau^2}{m_W^2} = 4.3 \times 10^{-6} \quad (24)$$

This is consistent with (22). Therefore we have

$$\tau = \frac{10^{44} \text{ s}}{[m'(\text{eV})]^5} \quad (\text{Extended GWS}) \quad (25)$$

It must be remembered that the mixing angles may increase this significantly (e.g., $\tau \rightarrow \infty$ if $\theta_1 = 0$).

C. Heavy Lepton

The leptonic version of the Glashow-Iliopoulos-Maiani (GIM) suppression mechanism was operative in (22) and led to the $\mathcal{O}(m_\tau^2/m_W^2)$ numbers in (24). We can therefore achieve a larger decay rate by going to some model involving heavier leptons. (24) is changed to

$$|a|, |b| = \frac{3}{32\pi^2} = 10^{-2} \quad (26)$$

and so

$$\tau = \frac{10^{37} \text{ s}}{[m'(\text{eV})]^5} \quad (\text{Heavy Lepton}) \quad (27)$$

This agrees with detailed model calculations with an additional very heavy lepton^{23,24} (fourth generation) and was first estimated in Reference 8.

D. GIM-less

Models where the GIM mechanism is absent altogether could also decrease the lifetime to the order-of-magnitude (27). This is the conclusion of Reference 8 in a model involving an additional, weak SU(2) singlet neutrino and is also analyzed in Reference 23. We may write

$$\tau \approx \frac{10^{37} \text{ s}}{[m'(\text{eV})]^5} \quad (\text{NO GIM}) \quad (28)$$

with the caveat that this, as well as our other estimates, could be significantly larger if mixing angles are sufficiently small.

E. Majorana-Dirac Neutrinos

We may try to evade GIM suppression by considering both Dirac and Majorana mass terms in the Lagrangian, a circumstance which can arise in certain grand unified theories where the Majorana masses can be induced by radiative corrections. Cheng and Li²⁵ have studied the rates for $\mu \rightarrow e\gamma$ for these general neutrino mass eigenstates in an extended GWS model, and we can adopt their work to $\nu' \rightarrow \nu\gamma$. If all six of the masses are small, we still have GIM cancellations. If we choose three of the masses to be as large as we wish, a fine tuning of the parameters in a most general mass matrix can enhance the decay rate. However, we still see the same lower limit

$$\tau \gtrsim \frac{10^{37} \text{ s}}{[m'(\text{eV})]^5} \quad (\text{Majorana/Dirac}) \quad (29)$$

In this regard, see also Reference 23.

F. Higgs

Pal and Wolfenstein²³ have also pointed out that Higgs intermediate states could enhance amplitudes by a factor of $(M_W/M_\phi)^2$ where M_ϕ is a Higgs mass. If there is no GIM-like cancellation in the remaining factors, then we can optimistically guess that

$$\tau \gtrsim \left(\frac{M_\phi}{M_W}\right)^4 \frac{10^{37} \text{ s}}{[m'(\text{eV})]^5} \quad (\text{Higgs}) \quad (30)$$

In the case where $M_\phi/M_W = 0.1$, a four order-of-magnitude reduction would result.

G. Composite Models

There has been much effort in recent years constructing composite models of quarks and leptons out of more basic particles. Various models have been proposed. Many of these models naturally embrace non-zero mass neutrinos, especially if higher generations are viewed as some sort of excitation of the "ground state". Thus, it is very natural for us to focus on neutrino decay as a consequence of compositeness.

Unfortunately, the research area is quite new, and the problems of building very light particles with very small sizes and pointlike magnetic moments are immense. No model has yet appeared which is consistent with experiment and known theoretical constraints. For example, radial or orbital excitations with a mass scale of an inverse lepton or quark size should lead to much heavier higher generations than are seen. Therefore, we have no single calculation to offer as a good indication of what to expect for a decay lifetime. Even the $\mu \rightarrow e\gamma$ comparison is fraught with danger, in the context of compositeness. It is possible that the great differences mentioned later are due to entirely different constituents in the two cases.

We are able to obtain order of magnitude estimates for lifetimes if a scale Λ (composite size Λ^{-1}) is given. This holds for a reasonably large class of models, an important consideration since we want to be sure that there is no general principle which states that such electromagnetic decays of composite neutrinos is vanishingly small. For certain theories, the transition magnetic dipole moment is zero in chiral symmetry limits, and for others, the neutrino has neutral constituents. However, a variety of considerations⁴

indicates that the higher generations are best viewed as additional scalars or pairs tacked on to the lightest generation.

The smallest lifetime in those models whose neutrinos are fundamental fields corresponds to estimates like (30), yet still appears to be too large to account for any cosmic UV background flux observed. (The lifetime indicated by existing observations, under the assumption that neutrino decay is responsible for an observed flux enhancement, will be discussed later.) We propose, in this paper, that significantly smaller lifetimes can be found in the case where the neutrino is not elementary, and that UV observations may give the first evidence for composite structure of leptons.

The scale of $\approx 10^{13}$ GeV, for $m' = 10$ eV, obtained from equation (23), corresponds to structure on a distance scale $\hbar c/\Lambda \approx 10^{-27}$ cm. Is it possible that the neutrino has a size much larger than this? There are, in fact, reasons to believe that leptons and quarks are bound states of something else, reasons having to do with the proliferation of particles and parameters in grand unified theories, the fact that the three generations resemble a bound state spectrum, the mismatch with supersymmetry multiplets, and so forth. This topic has been reviewed nicely by Harari⁴ and has been the subject of many papers recently. Although neutrino radiative decay has not been studied, we have surveyed the general models proposed and give our estimates for τ below.

We may identify our Λ with the characteristic scale discussed by Harari⁴. Since no structure for leptons or quarks has yet been seen, we have only a rough idea of Λ , based largely on lower limits. The value

$$\Lambda \gtrsim 1\text{--}10^3 \text{ TeV} \quad (\text{magnetic moment, scattering}) \quad (31)$$

is most often quoted, based on the absence of non-QED anomalous magnetic moments and on the absence of evidence for quark and lepton structure in present scattering data, and on theoretical Higgs compositeness. The limits on the proton decay rate and the radiative muon decay rate give much more severe limits, with

$$\Lambda \gtrsim 10^8 \text{ TeV} \quad (\text{Limits on other decays}) \quad (32)$$

or even as high as the grand unification mass of 10^{15} GeV if the proton decay amplitude is first-order in Λ^{-1} .

The general decay rate for $\nu' \rightarrow \nu \gamma$ can be written

$$\Gamma = \frac{g^2}{\Lambda^2} \left(\frac{m'^2 - m^2}{m'} \right)^3 f\left(\frac{\Lambda}{m'}, \dots\right), \quad (33)$$

which introduces f and includes equation (18) as a special case. The point is that equation (17) is the amplitude for a magnetic dipole (M1) transition, and other possibilities may arise for composite fields and their effective Lagrangians. The dimensionless function $f(\frac{\Lambda}{m'}, \dots)$ may have other scales (entering as ratios in its argument). As a first guess, $f = \text{const} = 1$ (M1 transition) gives (for $m' \gg m$)

$$\tau = 10^{11} \frac{[\Lambda(\text{TeV})]^2}{[m'(\text{eV})]^3} \text{ s} \quad (\text{First-order}) \quad (34)$$

where the amplitude is $\sim em'/\Lambda$, first order. A second-order result would be

$$\tau = 10^{35} \frac{[\Lambda(\text{TeV})]^4}{[m'(\text{eV})]^5} \text{ s} \quad (\text{Second-Order}) \quad (35)$$

if Λ is the only other scale.

In the composite approach, protons are composites of composites and there are various ways in which its decay may be inhibited, with no direct implication for $\nu' \rightarrow \nu\gamma$ decays. On the other hand, $\mu \rightarrow e\gamma$ is much more closely related in structure and we may write

$$\Gamma(\mu \rightarrow e\gamma) = \frac{g}{\Lambda^2} \left(\frac{m_\mu^2 - m_e^2}{m_e} \right)^3 f_\mu \left(\frac{\Lambda}{m'}, \dots \right). \quad (36)$$

De Rújula and Glashow⁸ relate the two decays by

$$\tau \approx \left(\frac{m_\mu}{m'} \right)^3 \tau(\mu \rightarrow e\gamma) = \left(\frac{m_\mu}{m'} \right)^3 \frac{\tau(\mu \rightarrow e\nu\bar{\nu})}{B(\mu \rightarrow e\gamma)} \quad (37)$$

which, in our discussion, corresponds to $f = f_\mu$, a first-order approach. The lower limit²⁶ on the $\mu \rightarrow e\gamma$ branching ratio of 1.9×10^{-10} and the $\mu \rightarrow e\nu\bar{\nu}$ lifetime of 2×10^{-6} s combine to yield

$$\tau \gtrsim \frac{10^{28} \text{ s}}{[m'(\text{eV})]^3} \quad (\text{Composite Lower Limit (?)}) \quad (38)$$

This may be regarded as a conservative lower limit on the lifetime we could expect from composite models.

We should remember, however, that f and f_μ may be very different since we have been talking about neutrinos which have no charge, far smaller mass than muons and perhaps a Majorana character. Anything can happen at this point. In our previous discussions of extended GWS models the presence of a charged very heavy lepton eliminates GIM suppression for $\nu' \rightarrow \nu\gamma$, but, we now note, does not eliminate GIM suppression for $\mu \rightarrow e\gamma$. In this very heavy lepton model, $f/f_\mu = \mathcal{O}(10^8)$! The composite picture may even involve selection rules which operate differently in the two cases.

To demonstrate this, we give the following representative calculation. Suppose that the ν is a bound state of a fermion and a boson with masses m_f and m_b and charges e and $-e$, respectively. We may then estimate the transition magnetic moment by the lowest order perturbation calculation of the anomalous magnetic moment which appears in Shaw, Silverman and Slansky²⁷. We find, in the notation of equation (17) that

$$\frac{a}{\hbar} = \frac{ig'g}{16\pi^2} \left(\frac{m_f}{m_b} \right) (1 + \ln r) \quad (39)$$

where r is defined to be $m_f^2/m_b^2 \ll 1$. Here g and g' are the couplings between the neutrino composites and the two-particle states, and we have chosen $m_f \ll m_b$. If $m_b = 10^3$ TeV, $m_f = 10^2$ TeV and $g = g' \approx 1$ as some sort of hyperstrong interaction, then we get

$$\tau \approx \frac{10^{22} \text{ s}}{[m'(\text{eV})]^3} \quad (40)$$

Obviously, equation (40) is hardly a universal estimate and much smaller lifetimes can be found for other "reasonable" m_b and m_f . If it is accepted that the μ and ν cases are not trivially related ($f \neq f_\mu$) then we see that there is much freedom in composite models concerning lifetime estimates and the conservative lower limit given by equation (38) and in Figure 4 may not hold.

V. ULTRAVIOLET BACKGROUND DATA

The observational situation regarding the cosmic ultraviolet background fluxes, particularly at high galactic latitudes, is still in a relatively primitive state owing to fundamental observational difficulties. These

observations have been reviewed quite recently²⁸ and the reviews point out, among other things, conflicts in both observations and interpretation. Nevertheless, the contributions from various sources of background contamination can be estimated and general cosmic flux levels can be established. Although it was originally suggested that the UV flux from decay of neutrinos in the galactic halo would have a peak intensity in the direction of the galactic center⁸, fluxes from stars and a large dust opacity make searches in this direction impractical. Rather, one should look in the direction of the galactic poles where these effects are minimized²⁹. Indeed, significant portions of the sky near the galactic poles may be almost totally free of dust³⁰ (a fact which is also important to studies of the cosmic far infrared background³¹).

The UV observations may be summarized as follows³²: With all numbers in units of photons $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{\AA}^{-1}$, the diffuse high-latitude far UV spectrum appears to be flat between $\sim 1300 \text{\AA}$ and $\sim 1525 \text{\AA}$ with an intensity of 260 ± 40 . (Allowance for up to 0.2 mag of extinction by high latitude dust could bring this number up by as much as 20 percent, but this is still within the error of the measurements.) In the range between 1680\AA and 1800\AA , the mean flux level increases to ~ 600 . The big question here is how much of the flux could be from such things as scattered starlight, airglow, and the integrated flux of distant galaxies. It has been argued that backscattering of starlight is negligible³³, however, this is presently a point of contention³⁴. The $\sim 1700 \text{\AA}$ feature is not consistent with calculations of the spectrum from distant galaxies³² but may be due to airglow (another point of contention). In the next section, we will use the "flat" flux level to derive a lower limit on the neutrino lifetime, and we will also discuss the possibility that the $\sim 1700 \text{\AA}$ feature may be from neutrino decay²⁹ and the implications of this hypothesis.

VI. ASTROPHYSICAL LOWER LIMITS ON τ AND OTHER ASTROPHYSICAL IMPLICATIONS:

By making use of equation (16), the measurements of I_λ discussed in section V can be used to place lower limits on τ . The most stringent limits are obtained for the case $\Omega = 1$ ($I_\lambda \propto \lambda^{-5/2}$) and using the data at the shortest wavelengths. For this purpose, we take³⁵

$$I_{1250 \text{ \AA}} \lesssim 200 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ \AA}^{-1} \quad (41)$$

Most previous workers³⁶ when using measurements or limits of the background radiation at various discrete wavelengths to obtain $\tau(E_0)$ or $\tau(m_\nu)$ have erred in connecting these discrete points to generate a smooth function $\tau(E_0)$. This method can be quite misleading, as it fails to account for the fact that local neutrino decay emission would occur in very narrow lines ($\Delta\lambda \sim 1 \text{ \AA}$) at specific wavelengths not covered by the data set used (see Figure 3a). There is, however, a way to obtain a correct continuous function $\tau(E_0)$ by utilizing the fact that cosmological neutrinos produce a redshifted continuum spectrum given by equation (15). Figure (3b) shows the characteristic triangular shaped spectrum obtained on a $\log I_\lambda - \log \lambda$ plot obtained from equation (15) if neutrino decay at an observation wavelength corresponding to point 0 is responsible for the flux at 0 (solid triangle). However redshifted radiation from the decay of higher mass neutrinos can also account for the flux at 0 (dashed triangle). The triangles are inverted on a $\log \tau - \log m_\nu$ graph (see Figure 3b). Adding together the limits thus obtained from flux measurements at several wavelengths gives a typical zig-zag limit function for $\tau(m_\nu)$ as indicated in Figure 3c. The resulting limit function from observational data over the whole frequency range of interest (infrared-

optical-ultraviolet)³⁷ is shown in Figure 4. The limits obtained from actual photon flux measurements correspond to the line labeled SB_F . For data compilations where the fluxes are given in units of $F(\text{erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ Hz}^{-1})$, the individual sections of SB_F are given by the formula

$$h_o \tau_{\min}(E_o) = 517 F_{\nu_{\text{ob}}}^{-1} (h\nu_{\text{ob}}/E_o)^{5/2} \eta_+(E_o - h\nu_{\text{ob}}). \quad (42)$$

where $h\nu_{\text{ob}}$ is the energy corresponding to the frequency of the observation ν_{ob} and η_+ is the Heavyside function:

$$\eta_+(x) = 1 \text{ for } x > 0 \text{ and } \eta_+(x) = 0 \text{ for } x < 0.$$

In the case where $E_o > 13.6 \text{ eV}$ (the Lyman limit $\lambda_o < 912 \text{ \AA}$) the decay photons are not generally directly observable (however, see footnote 41 later), but the indirect ionizing properties of the photons can be used to place limits on the decay time. This can be done by requiring that photoionization of high velocity clouds of neutral hydrogen (HI) near our galaxy not exceed observational limits³⁸.

Utilizing the condition that the ionization rate from ν -decay photons not exceed the recombination rate, Melott and Sciama³⁹ obtain the lower limit

$$\tau > (4 \times 10^{22} \text{ s}) \left(\frac{T}{10^4}\right)^{3/4} \frac{n_{\text{HII}}^2}{d} \left(\frac{\phi}{0.05}\right) \left\{ \frac{30 \text{ eV}}{m'} + h_o^{-1} \left[1 - \left(\frac{\lambda_o}{912 \text{ \AA}}\right)^{3/2}\right] N \right\} \quad (43)$$

where n_{HII} is the density of ionized hydrogen in cm^{-3} , T is temperature, d is the distance of the cloud in kpc, ϕ is the angular extent of the cloud on the sky, m' is in eV and N is the number of ionization per photon. Equation (43) gives a conservative lower limit on τ of $\sim 10^{24} \text{ s}$ if the clouds are at a distance of $\sim 1 \text{ kpc}$.

Another method of computing τ from ionization arguments is to note that the lifetime of the clouds $T_{c1} > 10^{14}$ s. In order for the clouds to exist in their neutral state, the ionization rate Γ_i must therefore be low enough such that the photons cannot eat through the cloud in a time T_{c1} . Therefore, the flux from neutrino decay F_Y^ν must satisfy

$$F_Y^\nu T_{c1} \lesssim n_{HI} \ell \quad (44)$$

from which a rough limit is obtained on the neutrino lifetime

$$\tau \lesssim 4 \times 10^{23} \text{ s} \quad (45)$$

in agreement with that obtained from equation (32).

The limits obtained from equations (43) and (44) are also shown in Figure 4. These limits can be compared with the limits given by equation¹⁵. Equations (43) and (44) only refer to the wavelength region $\lambda < 912 \text{ \AA}$ which represents $m' > 27.2 \text{ eV}$. The decay of lighter mass neutrinos, of course, will not produce ionizing radiation. It should be noted that if the high velocity clouds originate in the galactic plane, they could be continually in the process of "evaporating" by ionization once they leave the protection of the galactic disk. They can therefore start out with higher values of $n\ell$ than observed. Also the corona of ionized plasma which would form around the neutral core of the cloud could significantly slow the ionization rate (the Felten-Bergeron effect³⁹). Both these considerations could make the limits obtained from equations (43) and (44) somewhat too restrictive, but we assume here that they are "reasonable" to within an order of magnitude.

Having summarized the limits on τ in Figure 4, we now discuss the interesting conjecture that the $\sim 1700 \text{ \AA}$ feature (see section V) could be due to neutrino decay²⁹. This feature could then be hypothesized to be from a decay line somewhere in the band pass region of the photometers of Maucherat-Joubert, et al. and Anderson et al.,³³, i.e., in the wavelength range 1680 \AA - 1800 \AA corresponding to an energy range 6.9-7.4 eV and a neutrino mass m' in the range 13.8-14.8 eV. Of course, such neutrinos would have all of the desirable cosmological properties discussed in Section II by satisfying the condition (6). The line would have an expected width $\sim 2 \text{ \AA}$ and for neutrinos in a large galactic halo would require a neutrino lifetime $\approx 6 \times 10^{24} \text{ s}$ (points on Figure 4). This lifetime is within the limits obtained from our astrophysical arguments; however, it is much shorter than that given by the "standard" calculations (see Figure 4). But within the framework of the new substructure models for leptons and quarks (see Section IV) such decay rates are possible.

Thus, if the $\sim 1700 \text{ \AA}$ feature or some similar feature, shown by future observations to be narrow, could be shown to be from neutrino decay, it would be a test which would determine neutrino mass from equation (8) or (9) and may be the best way to prove that substructure for leptons and quarks exists⁴⁰. We therefore urge that improved high galactic latitude searches be made with a field-of-view small enough to exclude hot stars and dust patches and with good spectral resolution. We also suggest that such searches should begin with the 1680 \AA - 1800 \AA region⁴¹.

REFERENCES AND FOOTNOTES

1. The literature heretofore on this subject uses either the phrase "non-zero neutrino rest mass" or the adjective "massive". The former phrase is technically accurate but cumbersome. The adjective "massive" in standard English usage connotes heavy, bulky, or large objects. For example, a "massive neutrino expert" would be either a person knowledgeable in the physics of heavy neutrinos or a neutrino physicist weighing ~ 150 kg (330 pounds, 23 stones). The adjective "massy" seldom used, has an even more pronounced connotation in this direction. We prefer here to coin the adjective "massious" (having the property of mass) as more appropriate for present physics usage.
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41. Recently, preprints by Sciama and Sciama and Melott have come to our attention which conjecture that decay of ~ 100 eV neutrinos could

provide a source for ionizing the intergalactic medium and for ionization in the active halo. Cruddace et al. (Astrophys. J., 187, 497 (1974)) have shown that some radiation at such wavelengths (~ 2500 Å) may be directly observable in very restricted regions of the sky where the hydrogen column densities are known to be abnormally low owing to the opacity of hydrogen dropping off steeply with energy for photon energies above the Lyman limit. Another recent discussion of ionization of galactic and intergalactic gas by photons from this decay of 30eV-150eV neutrinos is given by Raphaeli and Szalay (Preprint NSF-ITP-81-52). They find $\tau \leq 10^{24}$ s in agreement with the results shown in Figure 4. They also show that in the case $\tau \ll 10^{24}$ s (higher ionizing fluxes) would have serious consequences for the evolution of the universe.

FIGURE CAPTIONS

- Figure 1. Mass/Luminosity ratio in solar units as a function of cosmic scale size. For extragalactic objects the dependences on h_0 are as shown on the scales.
- Figure 2. Feynman diagrams for radiative neutrino decay for GWS models with neutrino mixing.
- Figure 3. Improper and proper methods for obtaining $\tau(E_0)$ and $\tau(m_\nu)$.
 (a) Given a discontinuous set of data points $0, 0', 0'', \dots$ for I_λ at various λ , one cannot smoothly interpolate to get $\tau(m_\nu)$ (see text). (b) Cosmological continuum spectrum for redshifted emission generated by higher mass (----) and minimal mass (——) neutrinos to account for observation 0 and resulting $\tau(m_\nu)$ limits (see text). (c) Limits obtained from a set of observations $0, 0', 0'', \dots$ using the construction shown in (b).
- Figure 4. Theoretical model predictions for $\tau(m_\nu)$ and astrophysical lower limits on $h_0 \tau(E_0)$. (It is assumed that $m_\nu = 2E_0$, see equation (9). The limits marked SB_F (Stecker-Brown, this work) were obtained directly from cosmic photon fluxes. The limits MS_I (Melott-Sciama, Reference 38) and SB_I (this work) are from ionizing flux limits (see text). The point S is obtained from the $\sim 1700 \text{ \AA}$ feature (see Reference 29).







